STI Technical Report No. 137-3

ANALYSIS OF AIRCRAFT CARRIER MOTIONS IN A HIGH SEA STATE

W. A. Johnson

SYSTEMS TECHNOLOGY, INC.
Hawthorne, California 90250

March 1969

Prepared under Contract No. Nonr 4156(00)
for
OFFICE OF NAVAL RESEARCH, CODE 461
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FOREWORD

This report covers one phase of an overall program aimed at providing an analytic base useful in the development of improved carrier landing methods and systems. This phase deals with establishing a detailed knowledge of the nature of carrier motions in high sea states.

The program was directed by the Aeronautics Division of the Office of Naval Research and cosponsored by the Naval Air Systems Command under Contract Nonr 4156(00). The work was performed by Systems Technology, Inc., Hawthorne, California.

ABSTRACT

Carrier landing operations are often suspended due to severe deck motions. Attempts to compensate for deck motions require a detailed knowledge of the nature of such motions over short time intervals (because a landing approach typically lasts only 30 sec). This report contains the results of examining ship motion amplitude and frequency characteristics over short time periods in rough sea conditions. Included are histograms and power spectral density plots of pertinent recorded ship motions. These are presented for several short intervals over a three hour period so that a variation of motion characteristics with time is evident.

CONTENTS

SECTION I

INTRODUCTION

Carrier landing operations are often suspended because of severe deck motions. Attempts are being made to compensate for deck motions (and thereby extend recovery operations to more severe sea states) for VFR conditions utilizing visual landing aids (e.g., Fresnel Lens Optical Landing System) and for all-weather fully automatic landings with SPN-42 ACLS, Mode I. The extent to which compensation is helpful is dependent on the nature of the ship motions relative to the capability of the compensated landing system. The nature of ship motions over <u>short time intervals</u> is particularly important in landing system design since a landing approach typically lasts only 30 sec. Yet the extant ship motion data reveal only long-term (hour or longer) average characteristics which ostensibly would not show design-pertinent amplitude and frequency variations with time.

Therefore, an analysis was carried out to determine information basic to system refinements for carrier landings. The analysis was specifically aimed at examining ship motion amplitude and frequency characteristics over short time periods in rough sea conditions. Extreme care was required to avoid the problems (and incorrect conclusions) commonly associated with short time spectral analyses. Included here are the results of the analysis using ship motion data recorded aboard the USS INDEPENDENCE (CVA-62) in January of 1966.* As such, the results are strictly valid only for FORRESTAL class carriers in high sea states. However, a similar analysis (Ref. 5), previously carried out for another class carrier, led to almost the same conclusions. Therefore, confidence in the generality of the results is greatly enhanced.

For stationary time series, the accuracy in computing power spectral density points at various frequencies is proportional to the length of run

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*Data was recorded through the efforts of LTV Electrosystems and NATC Patuxent River personnel. Appendix A presents some pertinent details concerning this data.

analyzed. Thus the spectra become less accurately represented as the data time base is made shorter. In particular, a run length of 30 sec (for example) would yield either extremely variable estimates of power or very poor frequency resolution in the dominant frequency band, 0.4 to 0.8 rad/sec. Therefore, a tradeoff was made between the desired short-time analysis, the need for reasonable confidence limits on the results, and the desired frequency resolution. By comparing the scatter of the data points for various effective run lengths, a minimum run length of approximately 6 min, and a frequency resolution of 0.05 rad/sec were selected as a compromise.

The original recorded data consists of five reels of magnetic tape containing FM signals of ship motion quantities. Each reel has about five hours of continuous ship motion data. The data analyzed here include the most severe of the recorded ship motions (estimated to be Sea State 6). Included are ten different 377 sec intervals taken from FM reels Nos. 3 and 4.

The analysis of the data was carried out via the "BOMM" program (Ref. 1) on a high-speed digital computer.* Of the eight ship motion variables presented here, only three (pitch, roll, and touchdown point displacement) were obtained directly from the original data. The other five were derived as linear sums of the above three (using ship geometry, etc.). Table I presents a list of the eight ship motion variables along with their definitions and positive directions.

Section II of this report contains a discussion and interpretation of the analysis results.

Section III consists of a short summary of conclusions and recommendations.

Appendix A presents a few pertinent details concerning the original data.

Appendix B presents some of the more technical aspects of the data reduction operations.

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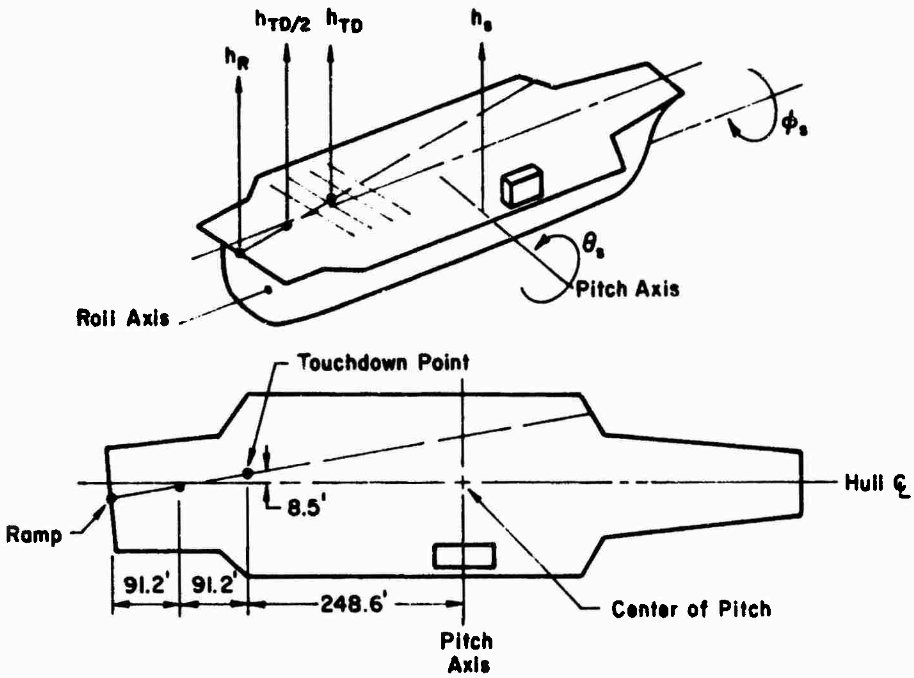
*Some details of the data reduction are included in Appendix B.

TABLE I

TERMINOLOGY AND AXIS SYSTEM DEFINITIONS

θ_S	Ship pitch angle (+ bow up)
φ_S	Ship roll angle (+ starboard down)
h_S	Ship heave (+ up) (The ship heave is defined to be the vertical displacement of the ship's center of pitch.)
h_{TD}	Touchdown point displacement (+ up) (The touchdown point is a particular point on the angled deck centerline between the No. 2 and No. 3 "wires".)
h_R	Ramp displacement (+ up)
$h_{TD/2}$	Displacement of point on deck halfway between touchdown point and ramp (+ up)
$\dot{h}_{TD}$	Velocity of touchdown point (+ up)
V_{I_S}	Impact velocity due to ship motion (+ for higher impact velocity) ($V_{I_S} = \dot{h}_{TD} + U_R\theta_S$ where U_R is the relative speed between the airplane and the carrier. Note that the impact velocity due to ship motion is not just the velocity of the deck at the touchdown point, but contains a contribution due to deck pitch angle. This deck incidence angle contribution is required because touching down with a bow-up deck, for example, is equivalent to a steeper glide path, as far as how hard you hit the deck is concerned.)



Appendix C contains plots of statistical properties of the ship motion quantities. These plots are histograms of the amplitude distribution for each variable. They are presented with the mean values removed, and thus indicate the distribution about the mean. The values of the means as well as rms deviations from the means are presented in a table for easy reference.

Appendix D contains power spectral density plots of the ship motion quantities.

SECTION II

DISCUSSION AND INTERPRETATION OF ANALYSIS RESULTS

A. TIME INTERVAL SELECTIONS

The ten time intervals selected for analysis are indicated in Fig. 1. By selecting the intervals as shown, it was possible to estimate the run-to-run variability in the data (e.g., file 19 versus 19A versus 19B) as well as the variability in the ship motion characteristics with time (e.g., file 15 versus 17, etc.). The pertinent ship and sea conditions (Ref. 2) during the selected intervals are given in Table II.

B. COMPARISON OF RESULTS

The largest ship motions were found to occur on FM Tape No. 4 (where peak displacement of the ramp exceeded 20 ft). Therefore, most of the

TABLE II

PERTINENT SHIP AND SEA CONDITION DATA

	STI FILE NO.	TIME INTO TAPE — TO FILE CENTER (HR:MIN)	SHIP HEADING	WAVES			SWELLS		
				DIRECTION	AMPLITUDE	PERIOD	DIRECTION	AMPLITUDE	PERIOD
FM TAPE NO. 3	7	3:15	110°	60°	9 ft	9 sec	100°	7 ft	7 ft
	7A	3:21							
FM TAPE NO. 4	15	1:41	320°	300°	10 ft	6 sec	NO SWELLS		
	15A	1:47							
	17	2:50	320°	340°	14 ft	6 sec			
	17A	2:56							
	19	3:53	320°	340°	14 ft	6 sec			
	19A	3:59							
	19B	4:05							
	20	4:25							

Note: These data were <u>estimated</u> by the ship's meteorology department each hour (on the hour) and were <u>not</u> the results of careful measurements.

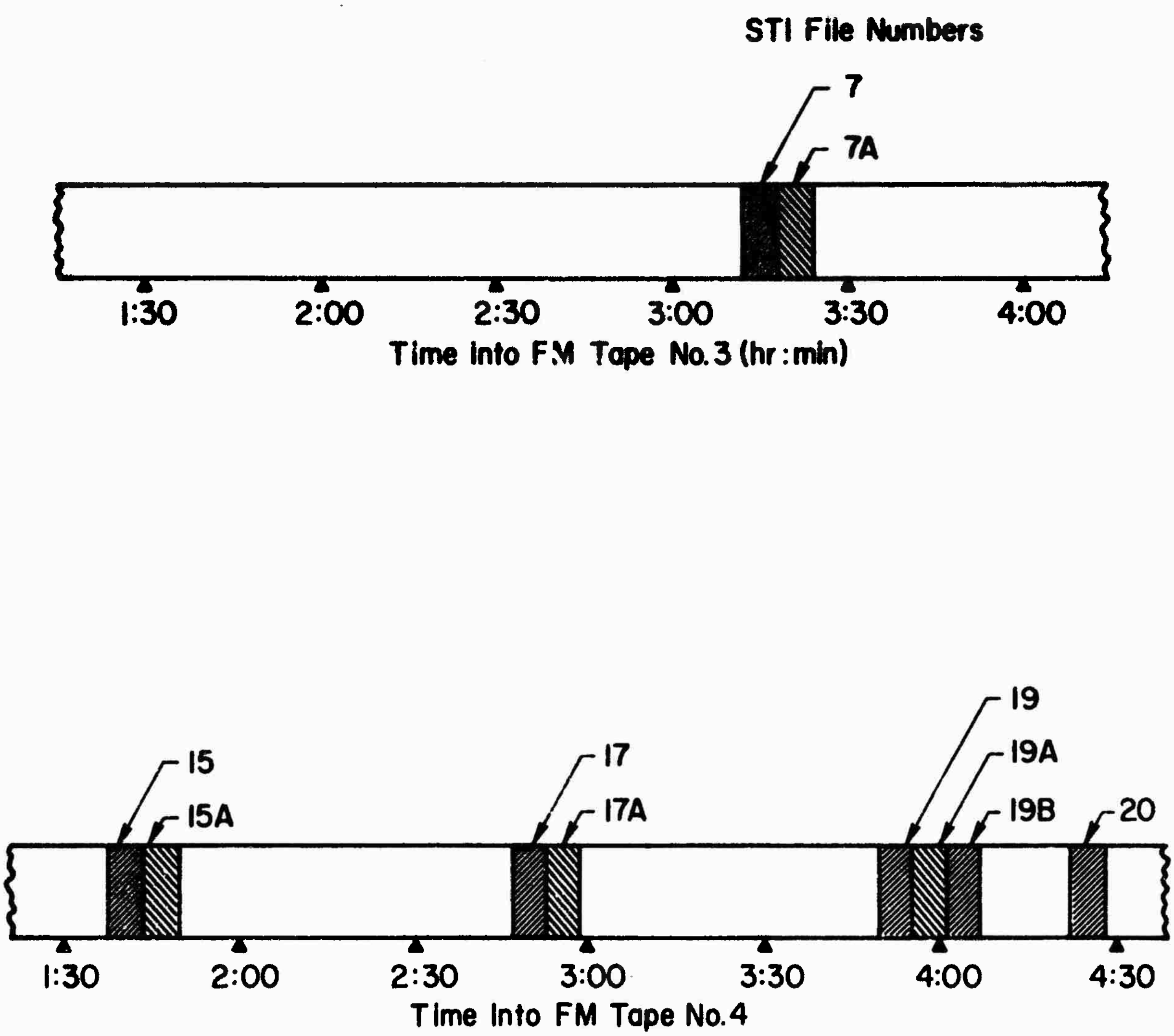


Figure 1. Time Intervals of Data Selected for Analysis

effort was concentrated on analyzing files 15 through 20. The analysis of files 7 and 7A was carried out merely for comparison purposes, because it was necessary to determine if the frequency characteristics associated with the relatively smaller motions were appreciably different from those of the large motions.

The results of the comparison can be summarized as follows. The sea conditions during the recording of files 7 and 7A included swells and sea waves, whereas the sea conditions during files 15-20 (corresponding to the following day) included only sea waves. However, comparisons of the ship motion power spectra from files 7 and 7A do not appear to be significantly different from those from files 15-20 (e.g., see Figs. D-1b and h, and D-3a, b, e, and j).

C. CORRELATION BETWEEN SHIP MOTIONS AND SEA CONDITIONS

By comparing the plots of rms motion versus time (in Figs. 2 and 3) with the sea observations (in Table II) it can be seen that the measured ship motions correlate roughly with the observed sea conditions. In particular, the rms values of the ship motion variables increase significantly during the time that the sea conditions were observed to increase.

D. MAGNITUDE OF SHIP MOTIONS DEPENDENT ON TIME

Because the amplitudes of the ship motions were increasing with time, they do not represent a stationary process (over intervals of the order of an hour). Therefore, statistical properties averaged over an interval of an hour or more (with this data) would not be appropriate descriptors of the ship motion. From Fig. 2 it appears that the maximum interval over which the stationarity assumption is reasonable (i.e., there is less than a 10 percent variation in the mean) is somewhat less than 30 min.

E. SHIP MOTION FREQUENCY BAND ALSO TIME-DEPENDENT

Having seen that the ship motion magnitudes were increasing by more than a factor of 2, it is interesting to learn that the frequency region in which most of the pitch power was concentrated decreased by about 20 percent. This is completely consistent with the theory of a developing

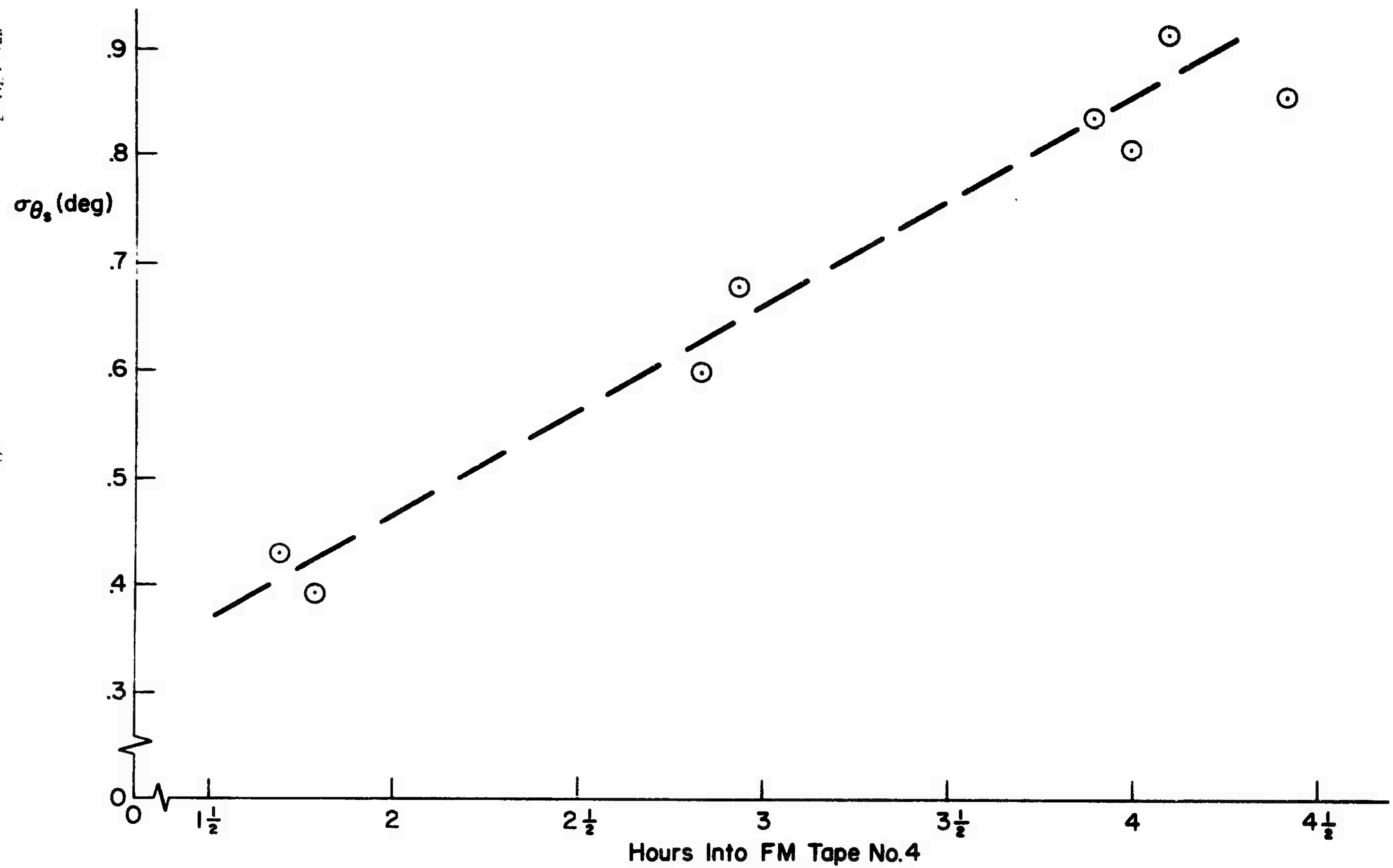


Figure 2. RMS Pitch Angle Versus Time

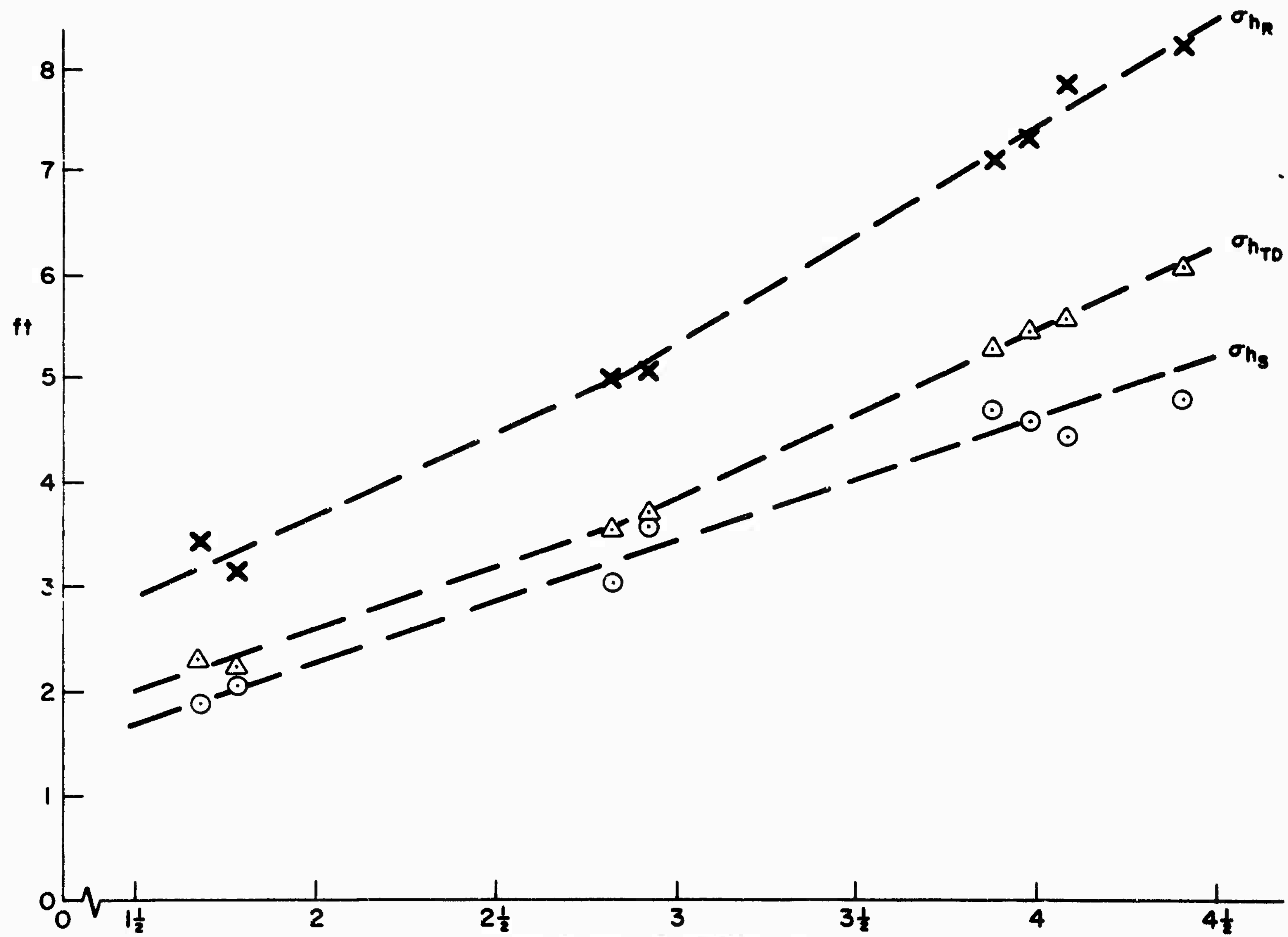


Figure 3. RMS Vertical Displacements Versus Time

sea state (Ref. 3), and is seen in Fig. 4a where the frequency regions for the largest pitching motions are plotted versus time. The frequency for the peak power is also noted on the plot. Figure 4b shows the frequency regions for the largest heave motions superimposed on the pitch angle plot. In general, the heave frequencies were the same or slightly lower than the pitch frequencies.

F. TIME-VARYING CENTER FREQUENCY

One of the more interesting aspects of the ship motions was the tendency for the power spectral density (PSD) plots of pitch angle to have two peaks in the region of maximum power (e.g., see Figs. D-1e and D-1f) The explanation for the multiple peaks is that several times during each 6 min interval the pitch motions would become very regular for a few cycles. However, the frequency would not be exactly the same each time these regular intervals occurred. Thus it was possible (and, in fact, likely) that during any short interval (such as a 6 min run) the regular oscillations would miss some part of the frequency band near the peak power, with the missing frequencies showing up in the next 6 min run. It can be seen that this is, in fact, the case by comparing the frequencies of the peaks in the PSD plots with the frequencies of the troughs between the peaks from run to run. If this is done, it is typical to find that the peak frequency in one run is the trough frequency in the next run. Also we'd expect that some of the file boundaries would fall between the regular-motion intervals in such a way that the PSD plot from one file would have a peak at one frequency and the adjacent file would have its peak at a different frequency (rather than multiple peaks being in every file). This exact situation occurred with files 15 and 15A (Figs. D-1c and D-1d).

The pronounced multiple-peaking found in some of the pitch PSD plots did not occur in either the roll or heave PSD's, indicating that the pitch motions are basically more narrowband (for head seas). Thus the intervals of regular motion are more common with pitch than with roll or heave. For reference purposes, Fig. 5 shows some typical time traces of ship motions.

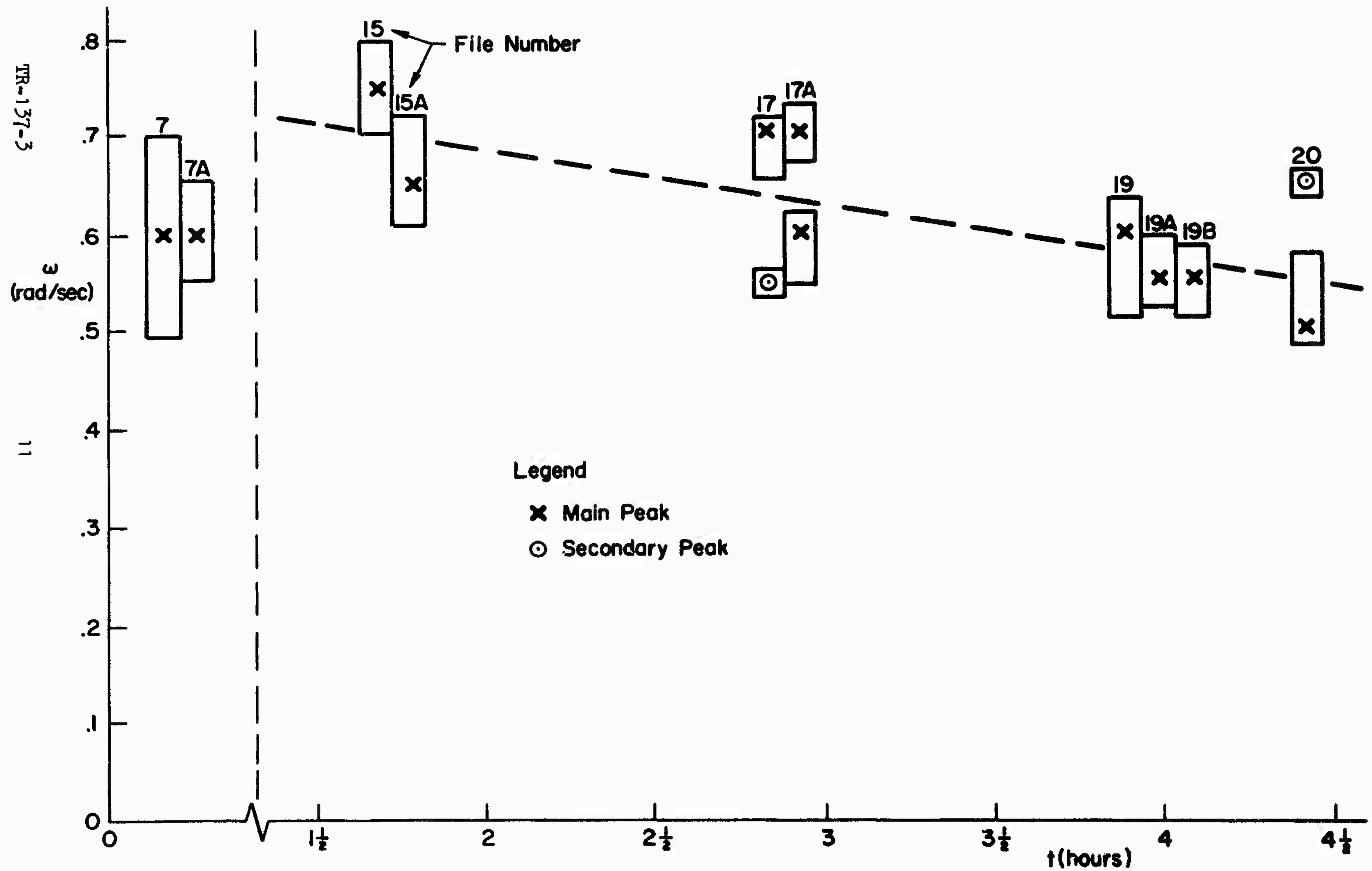


Figure 4a. Region of Most Power for Ship Pitch Angle (θ_s)

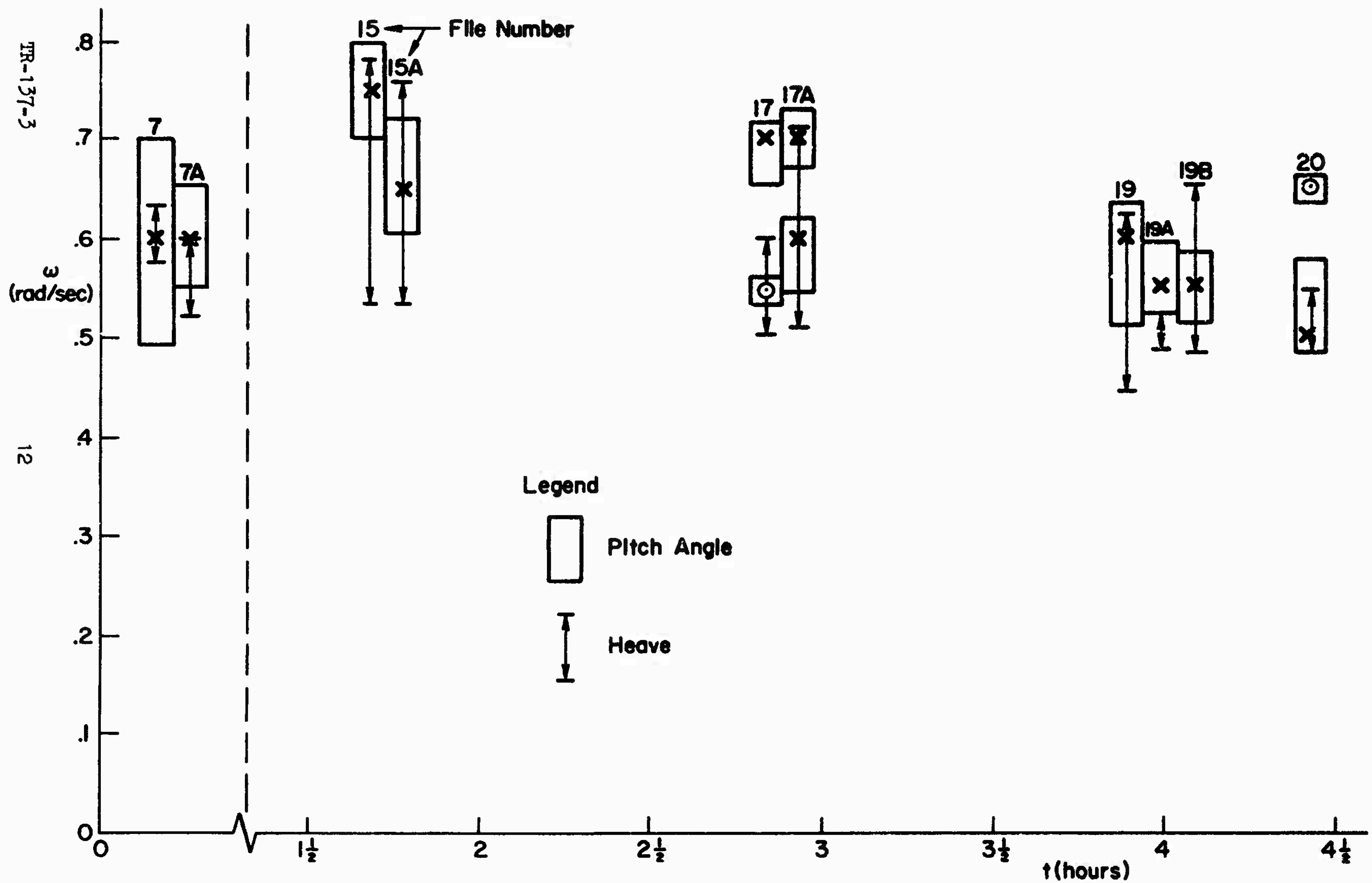


Figure 4b. Comparison of Regions of Most Power for Ship Pitch Angle (θ_s) and Ship Heave (h_s)

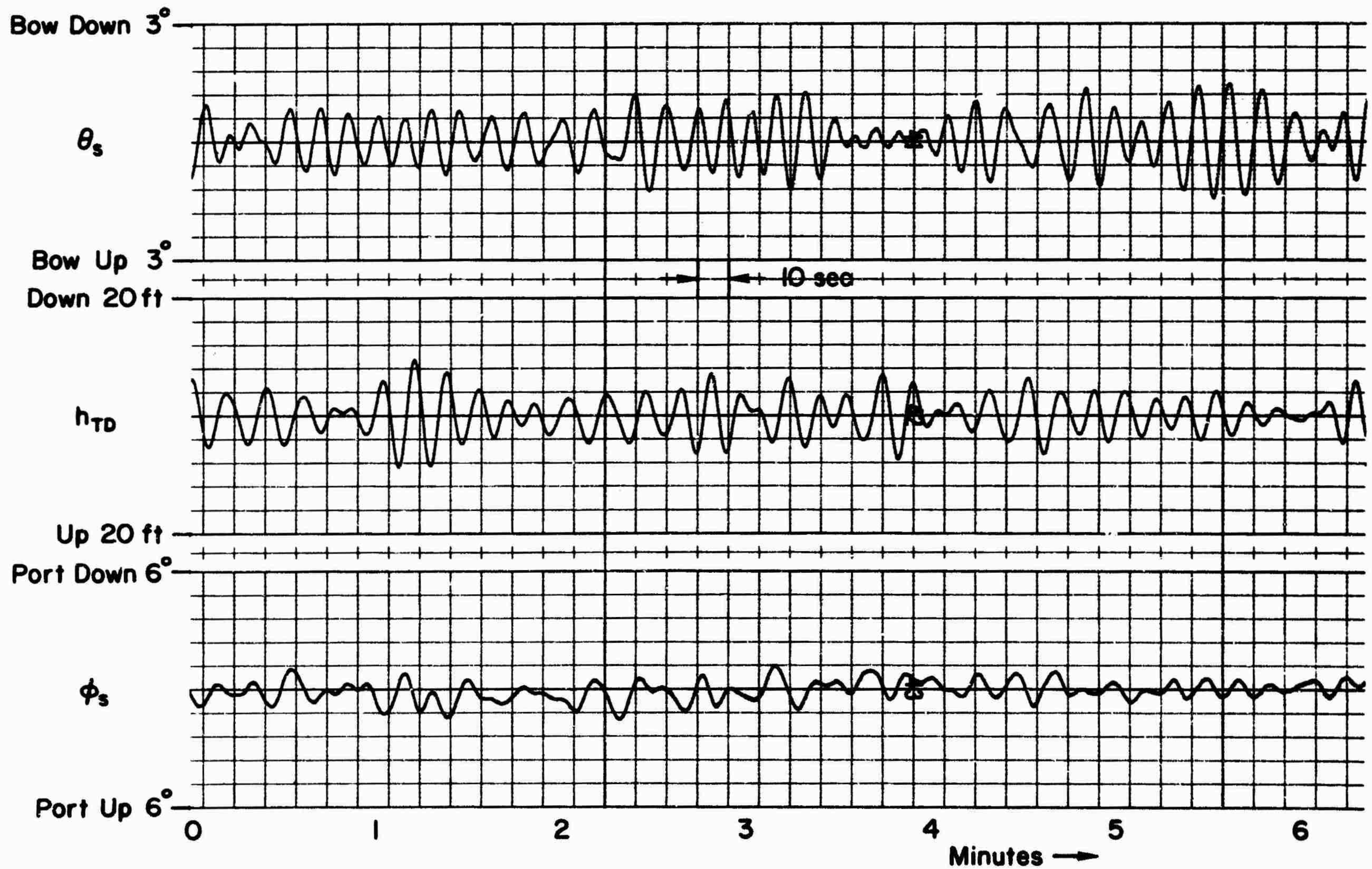


Figure 5. Time Traces of Typical Ship Motions; From File 17
(Scales are only approximate)

G. COMPARISON OF FREQUENCIES

Although the center frequencies moved around somewhat, it was generally found that in any one file the center frequency for pitch was greater than (or equal to) the center frequency for heave; and that the heave frequency was greater than (or equal to) the roll frequency.

H. ROLL PSD BROADER THAN PITCH OR HEAVE

The general shapes of the PSD plots show that the roll spectra are more broad and flat than the others. This is a result of predominantly head-sea conditions during the intervals selected for analysis. A case of a sea condition involving beam-waves was looked at (this case is not included here because of a questionable swell situation) and found to have a very narrow-band, highly peaked roll PSD. This is a well-known characteristic which results from the small roll damping (usually) found in Naval vessels (and other ships without stabilizers).

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

Because we were looking for only a few specific characteristics of the ship motions, a list of the major conclusions can be presented quite briefly.

- For pitch and heave motions the center-frequency (where most of the power is found) was typically between 0.5 and 0.7 rad/sec; and the bandwidth (to the half-power points) was typically between 0.1 and 0.2 rad/sec. Thus, the ratio of the bandwidth to the center frequency (which is a measure of "narrowbandedness") was around 0.3. This means the motion characteristics are essentially those of a narrowband process. (It is noted that these results are substantially the same as those obtained from similar measurements taken aboard the USS ORISKANY.)

- The rms value of ship pitch (σ_θ) increased at a rate of about 0.2 deg per hour as σ_θ went from 0.4 deg to 0.9 deg.

- As the magnitude of ship pitching motions increased by more than a factor of 2, the center frequency decreased by about 20 percent.

- The maximum values of pitch and heave during each of the time intervals analyzed were found to be approximately equal to the respective 3σ values for the interval.

Because the conclusions pertaining to the spectral characteristics are in such close agreement with those from a prior analysis (for a smaller carrier), further validation seems unnecessary. Therefore, it is recommended that the results included herein be used in future analyses that require a knowledge of large carrier motion characteristics. In addition to their applicability to carrier landing system analyses, the results should be useful in carrier simulations and in the design of tracking platforms (such as for a tracking radar or gun fire control).

REFERENCES

1. Bullard, E. C., F. E. Oglebay, W. H. Munk, and G. R. Miller, A USER'S GUIDE TO BOMM—A System of Programs for the Analysis of Time Series, Inst. of Geophysics and Planetary Physics, Univ. of Calif., La Jolla, Jan. 1966.

2. Run Log of Ship Motion Recordings made aboard USS INDEPENDENCE, CVA-62, Jan. 24-28, 1966.

3. Pierson, Willard J., Jr., Gerhard Neumann, and Richard W. James, Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics, U. S. Navy Hydraulic Office, H. O. Pub. No. 603, 1955.

4. Telecon between W. A. Johnson, Systems Technology, Inc., Hawthorne, Calif., and Robert Junke, Bell Aerosystems Corp., Buffalo, N. Y., Dec. 11, 1968.

5. AN/SPN-10 Carrier Landing System (U), Bell Aircraft Corp. Rept. No. 60003-012, Apr. 1959. (Report Confidential)

APPENDIX A

PERTINENT DETAILS CONCERNING THE ORIGINAL DATA

The FM recordings of the ship motion data were found to have a sign inconsistency between the $\ddot{z}$ signal and the "heave" signal. (They were "in phase" instead of "out of phase".) Further, it was determined that there was also a sign inconsistency between the recorded pitch and heave (this was determined by considering the phasing between the recorded pitch and "heave" motions). The inconsistencies were rectified by reversing the sign of the "heave" signal in the calibration run (on FM tape No. 3). (This alternative was preferred to reversing the signs of both $\ddot{z}$ <u>and</u> pitch.)

The original data was taken from the SPN-10 channel A installation. Pitch was measured at TP 13, and roll at R201. The outputs of three body-mounted accelerometers were measured as follows: $\ddot{x}$ from 9TB5-7, $\ddot{y}$ from 9TB5-9, and $\ddot{z}$ from 9TB5-11.

The three accelerometer signals were passed through SPN-10 resolvers to obtain $\ddot{h}_a$, which is the vertical acceleration of the accelerometer package. The vertical displacement of the accelerometer package was computed by passing $\ddot{h}_a$ through a filter designed to approximate a double integration. The transfer function of the filter is given in Eq. A-1, and is plotted in Fig. A-1.

$$\frac{h_a}{\ddot{h}_a} = \frac{3613s}{\left(\frac{s}{7.00}+1\right)\left(\frac{s}{0.0495}+1\right)\left[\left(\frac{s}{0.075}\right)^2+\frac{2(0.5)}{0.075}s+1\right]} \qquad \text{(A-1)}$$

The h_a signal was passed through SPN-10 circuitry to compute the vertical displacement of a point on the deck called the "touchdown" point. (For the USS INDEPENDENCE the touchdown point is on the centerline of the angled deck, 185.1 ft forward of the ramp — measured along the angled deck centerline.) The resultant signal (h_{TD}) was measured at A5P1 Pos Comp C. Although this signal represents the vertical motion of a particular point on the deck, it

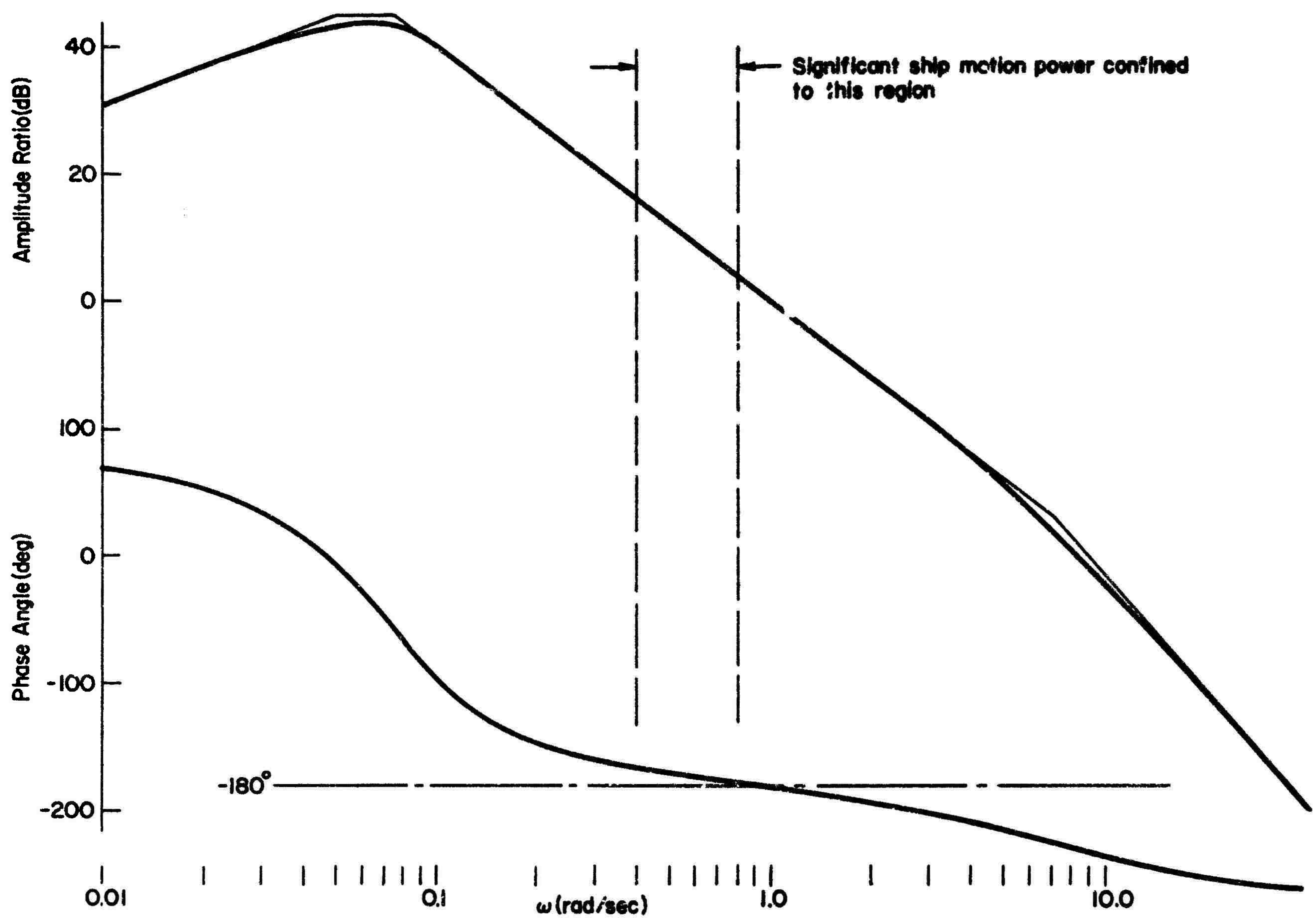


Figure A-1. Filter Used to Obtain h_a from $\ddot{h}_a$

was referred to as "heave" in the run log kept during the recording of the ship motions.

It is important to point out that it was not until one month **after** the recording of these motions that the SPN-10 h_{TD} signal on the USS INDEPENDENCE was modified by the addition of a term proportional to pitch angle (Ref. 4).

As a later check of the triaxial accelerometer resolution, the various angles and accelerations available on the FM tape were combined and integrated appropriately to produce a signal approximately h_{TD}. Then, by systematically reversing the signs of the angles involved, it was found that the best fit to the recorded h_{TD} was obtained when the signs were the same as those we had used in our analysis.

APPENDIX B

DIGITAL COMPUTATION DETAILS

To remove unwanted high-frequency noise, and to avoid aliasing, the FM data was filtered with a low pass filter (having a breakpoint at 1.09 Hz), and then digitized with a sampling rate of 6 samples/sec. The digitized data was then filtered (with a low pass filter having a breakpoint at 0.5 Hz) and decimated by a factor of 3 to give an effective sampling rate of 2 samples/sec. This filtering and decimation allows the data to be analyzed up to a frequency of about 3 rad/sec (which is beyond the frequency region of interest for carrier motions).

The minimum frequency at which power can be measured depends on the length of run analyzed. That is,

$$f_{min} = \frac{1}{T_R} \tag{B-1}$$

where T_R is the run length in seconds and f_{min} is in Hz.

By calculating the Fourier coefficients for a run length of 377 sec, a PSD plot could be obtained with a minimum frequency (which is equal to the frequency resolution) of 0.01667 rad/sec. Such a plot would have 2 deg of freedom per plotted point, and thus exhibit considerable scatter of the points. By combining the points in successive groups of three (with no overlap), a PSD plot can be obtained with a frequency resolution of 0.05 rad/sec, and 6 deg of freedom per plotted point (which gives less scatter of the points). This latter technique was used to obtain the PSD plots in Appendix D.

APPENDIX C

STATISTICAL PROPERTIES OF THE SHIP MOTION VARIABLES

Table C-I lists the mean value, the rms deviation from the mean, and the maximum absolute deviation from the mean for each of the variables of interest in the ten files analyzed. Table C-II follows with a list of the histograms that make up the remainder of this appendix. The histograms show the distribution of amplitudes for each of the ship motion variables (with the means removed).

TABLE C-I

SUMMARY OF MEAN VALUES, RMS DEVIATIONS FROM THE MEAN, AND MAXIMUM ABSOLUTE DEVIATION FROM THE MEAN FOR SEVERAL SHIP MOTION VARIABLES

	STI FILE NO.	θ_s (DEG)	ϕ_s (DEG)	h_s (FT)	h_{TD} (FT)	h_R (FT)	$h_{TD/2}$ (FT)	$\dot{h}_{TD}$ (FT/SEC)	V_{I_s} (FT/SEC)
MEAN VALUE DURING RUN	7	−0.07	0.92	0.08	0.52	0.24	0.38	0.02	−0.19
	7A	−0.07	1.06	0.17	0.65	0.29	0.47	−0.006	−0.22
	15	0.09	−0.82	0.16	−0.36	−0.20	−0.28	0.0005	0.27
	15A	0.09	−0.85	0.15	−0.35	−0.16	−0.25	−0.002	0.25
	17	0.09	−0.80	0.16	−0.36	−0.21	−0.28	0.001	0.28
	17A	0.09	−0.96	0.07	−0.46	−0.22	−0.34	0.02	0.28
	19	0.07	−0.95	0.09	−0.35	−0.04	−0.20	−0.002	0.20
	19A	0.06	−0.48	0.24	−0.09	−0.02	−0.05	0.02	0.19
	19B	0.08	−0.42	0.23	−0.16	−0.16	−0.16	−0.03	0.20
	20	0.07	−0.47	0.17	−0.22	−0.19	−0.20	0.03	0.25
RMS DEVIATION FROM MEAN	7	0.33	0.27	2.07	2.23	2.79	2.47	1.39	1.95
	7A	0.56	0.32	2.52	2.37	3.49	2.85	1.41	2.72
	15	0.43	0.36	1.91	2.32	3.35	2.79	1.50	2.34
	15A	0.39	0.36	2.04	2.27	3.13	2.65	1.51	2.41
	17	0.60	0.55	3.02	3.55	4.99	4.21	2.14	3.09
	17A	0.68	0.51	3.58	3.62	5.01	4.22	2.18	3.59
	19	0.84	0.99	4.70	5.28	7.12	6.10	2.90	4.57
	19A	0.81	0.96	4.54	5.45	7.35	6.32	3.38	4.80
	19B	0.92	0.80	4.42	5.54	7.79	6.58	3.17	4.96
	20	0.86	0.82	4.76	6.06	8.18	7.04	3.35	4.93
MAXIMUM ABSOLUTE DEVIATION FROM MEAN	7	0.97	1.06	7.26	6.65	7.86	6.08	4.15	5.25
	7A	1.64	1.09	6.25	7.36	10.2	8.73	5.11	8.40
	15	1.38	1.35	5.93	7.07	11.1	8.92	4.56	8.27
	15A	1.16	1.14	5.82	6.60	9.08	7.69	4.43	7.52
	17	1.47	1.57	9.82	10.0	12.1	11.1	6.46	8.09
	17A	1.70	1.47	10.4	9.46	13.6	11.3	6.12	9.83
	19	1.91	2.93	13.6	12.9	19.0	15.9	7.94	11.6
	19A	2.23	2.78	11.6	14.5	19.0	16.7	14.3	17.2
	19B	2.18	2.18	12.7	14.7	18.0	16.3	9.81	13.4
	20	2.52	2.11	10.5	14.4	20.9	17.0	8.4	13.5

TABLE C-II

LIST OF THE FILES FOR WHICH HISTOGRAMS ARE INCLUDED IN THIS APPENDIX

VARIABLE	FILES
[illegible]$_s$	17 , 20
φ_s	17 , 20
h_s	17 , 20
h_{TD}	17 , 20
h_R	17 , 20
$h_{TD/2}$	20
$\dot{h}_{TD}$	20
V_{Is}	20

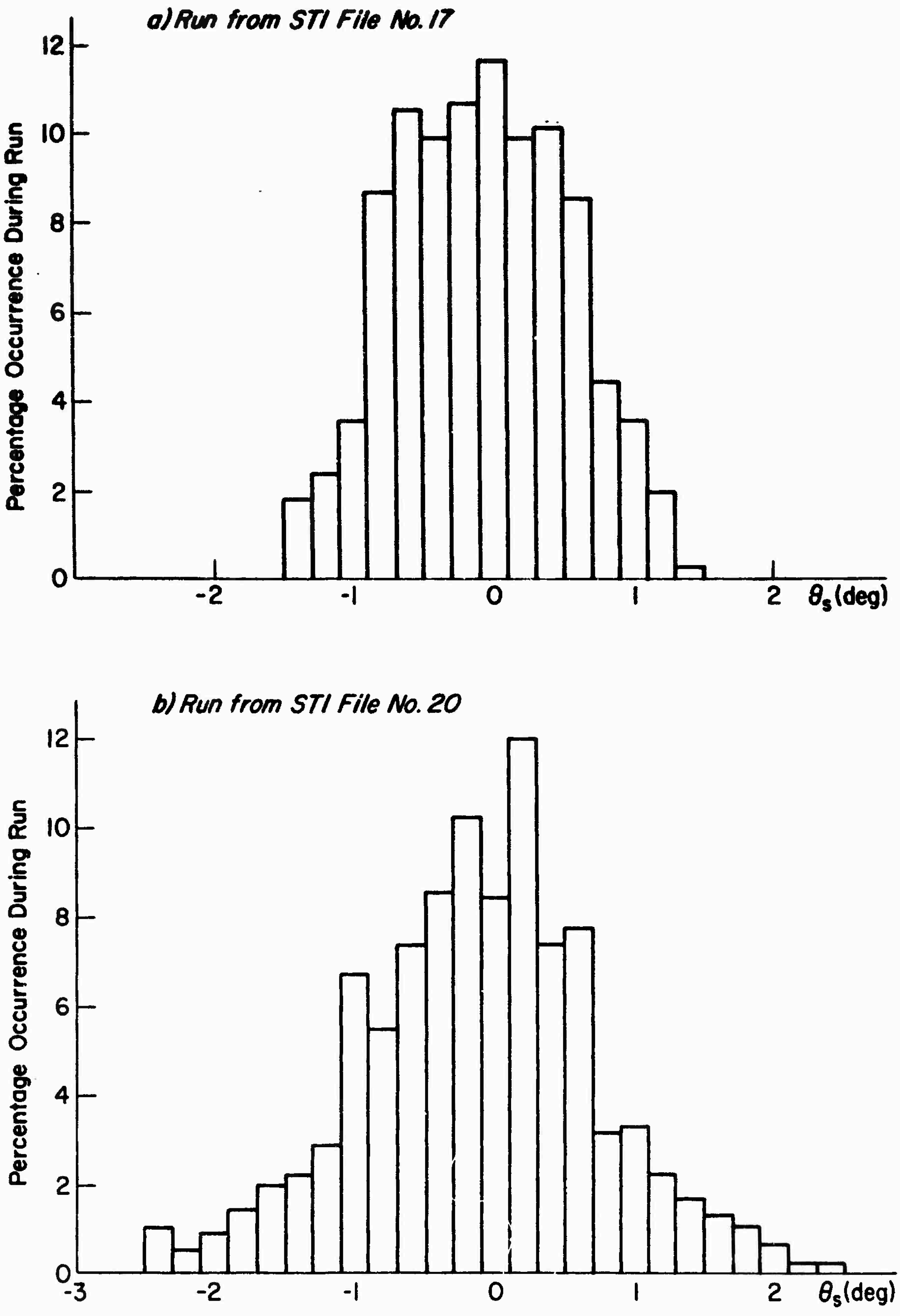


Figure C-1. Distribution of Amplitudes (From Mean) of Ship Pitch Angle (θ_s) in Degrees

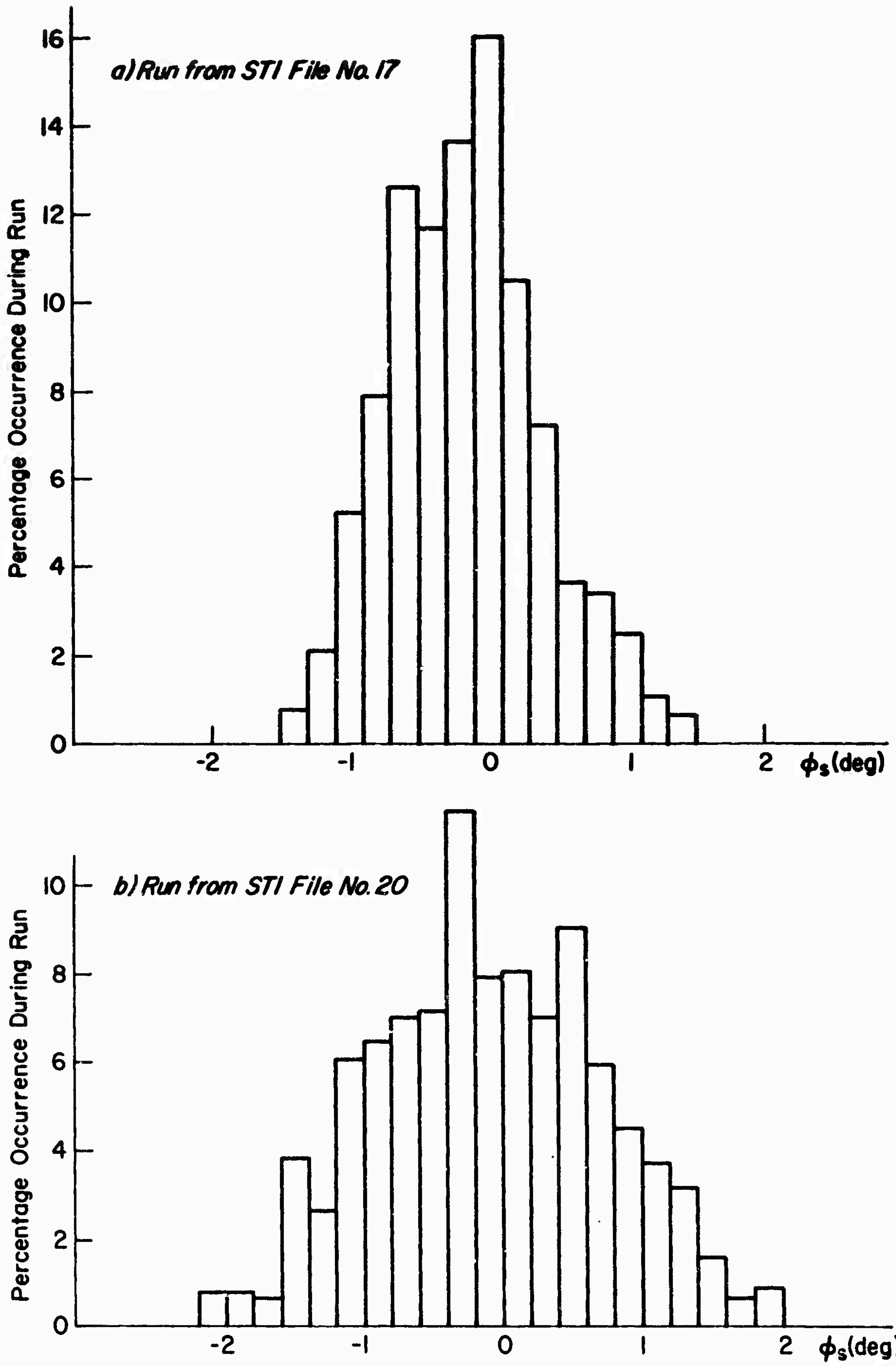


Figure C-2. Distribution of Amplitudes (From Mean) of Ship Roll Angle (φ_s) in Degrees

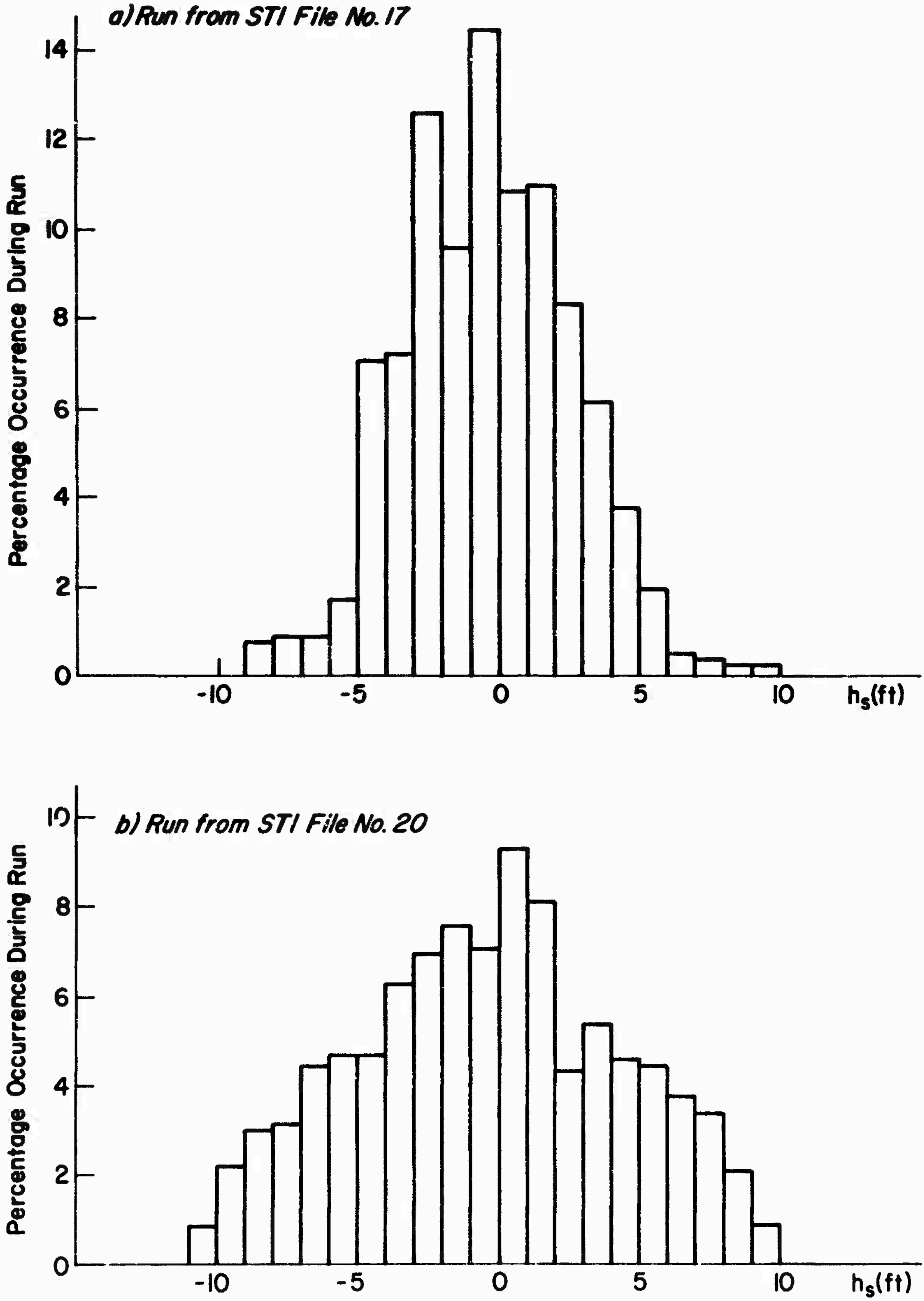


Figure C-3. Distribution of Amplitudes (From Mean) of Ship Heave (h_s) in Feet

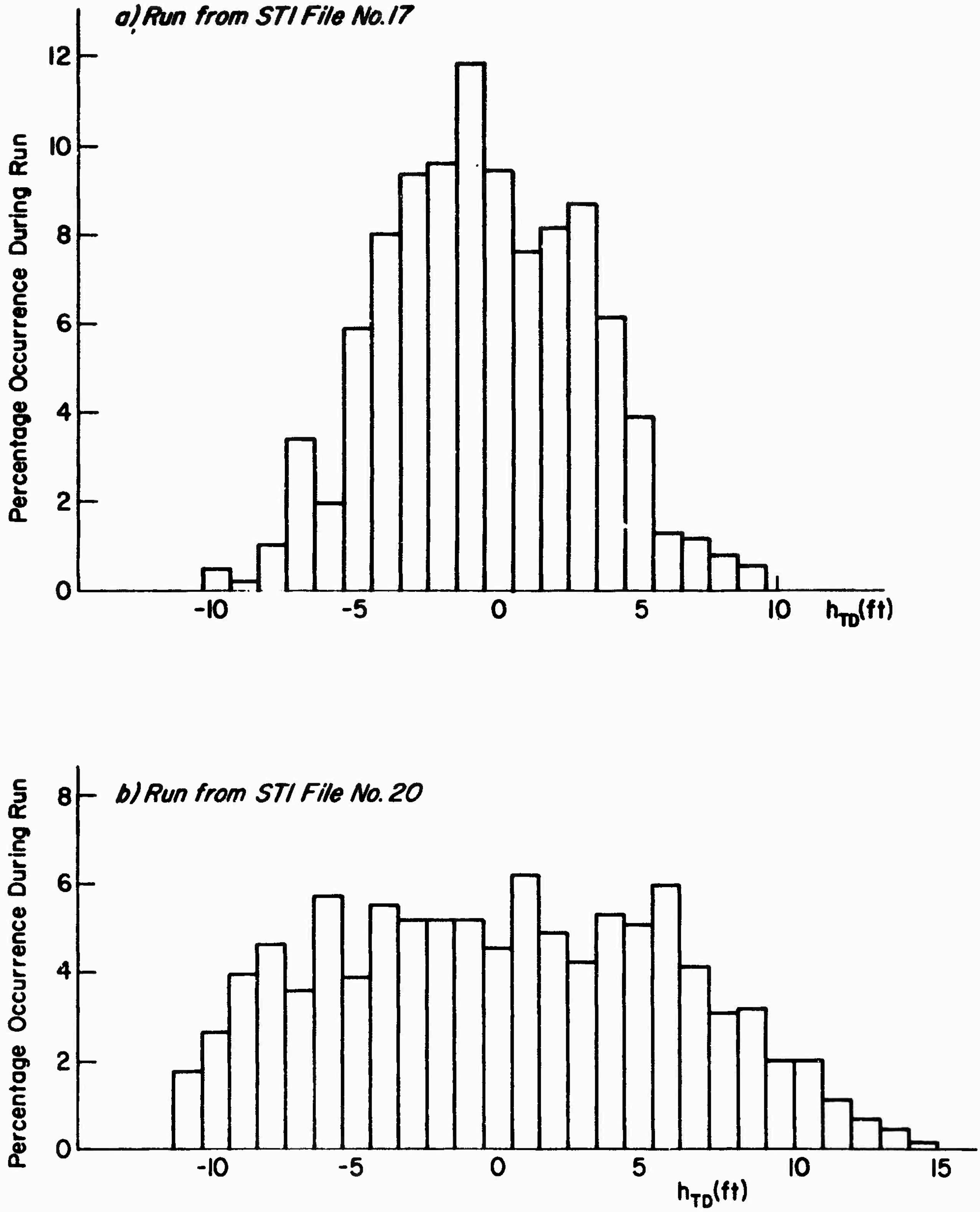


Figure C-4. Distribution of Amplitudes (From Mean) of Vertical Displacement of Touchdown Point (h_{TD}) in Feet

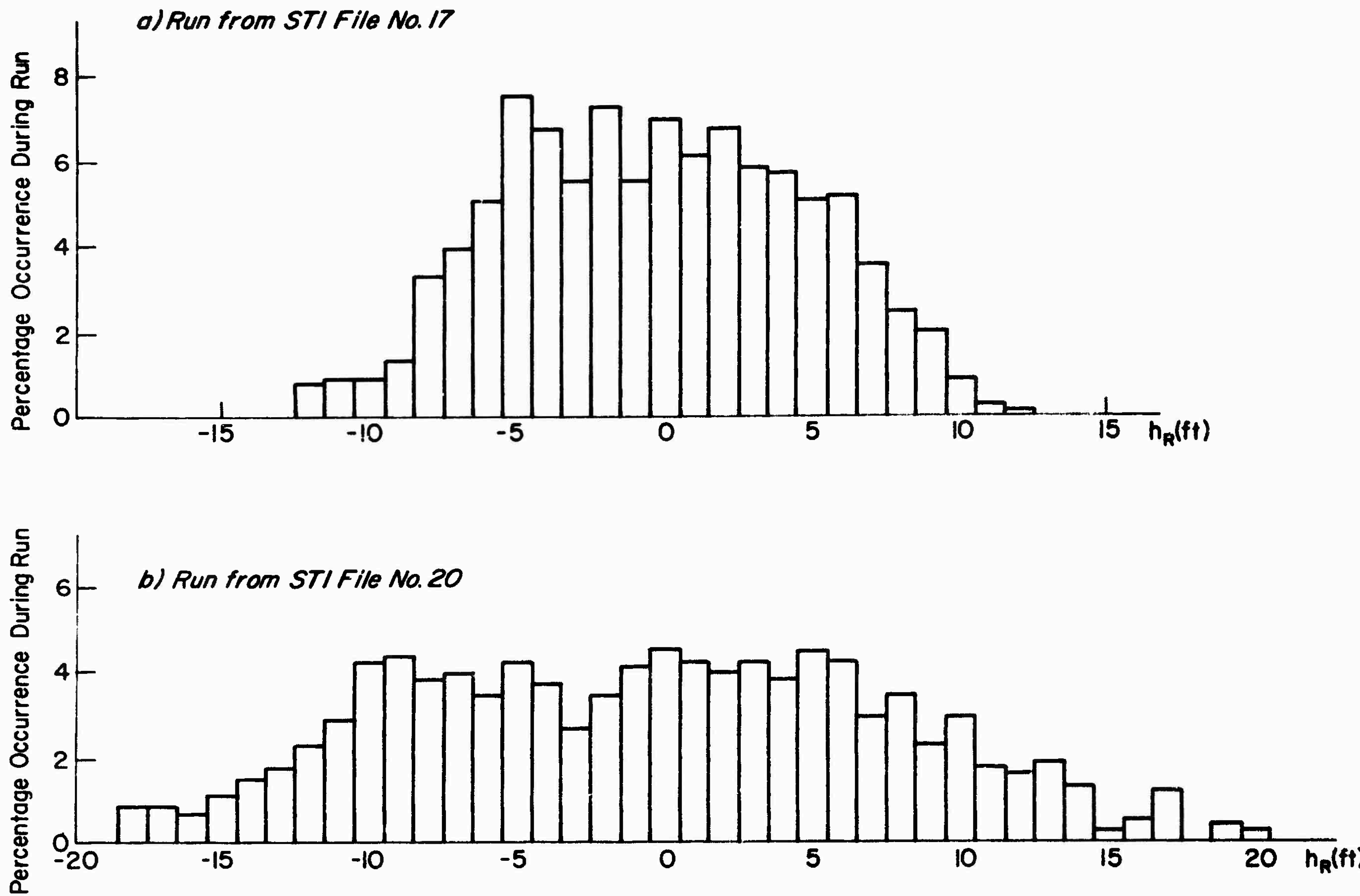


Figure C-5. Distribution of Amplitudes (From Mean) of Vertical Displacement of Ramp (h_R) in Feet

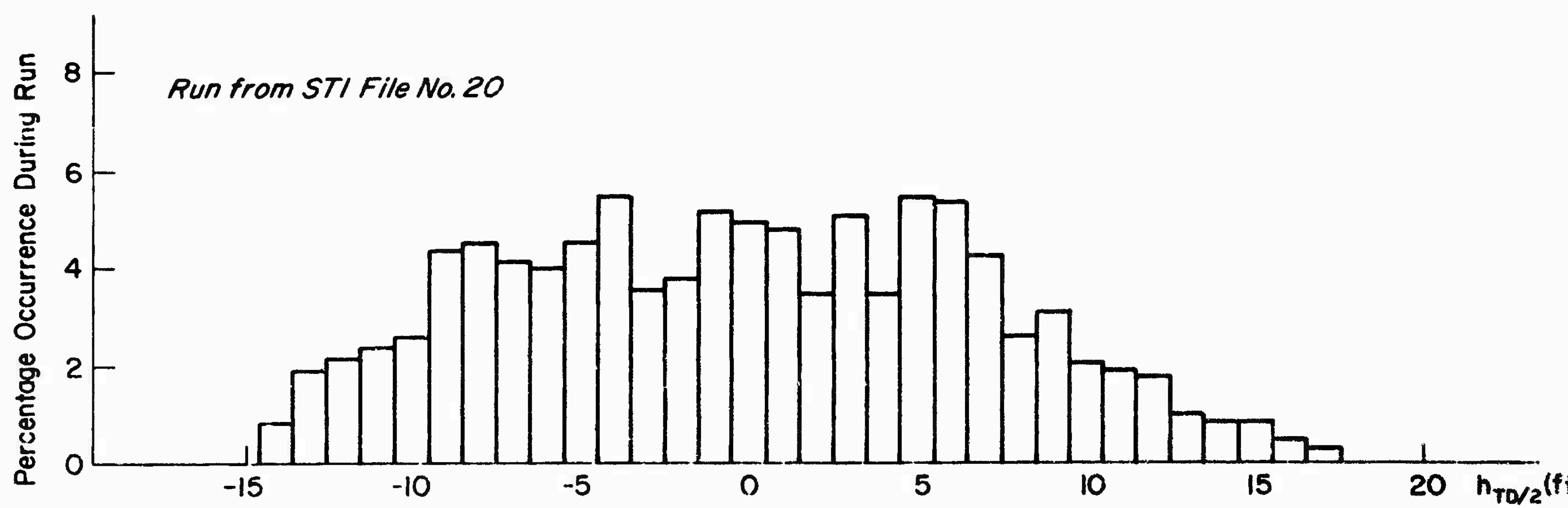


Figure C-6. Distribution of Amplitudes (From Mean) of Vertical Displacement of Point on Deck Halfway Between Ramp and Touchdown Point ($h_{TD/2}$) in Feet

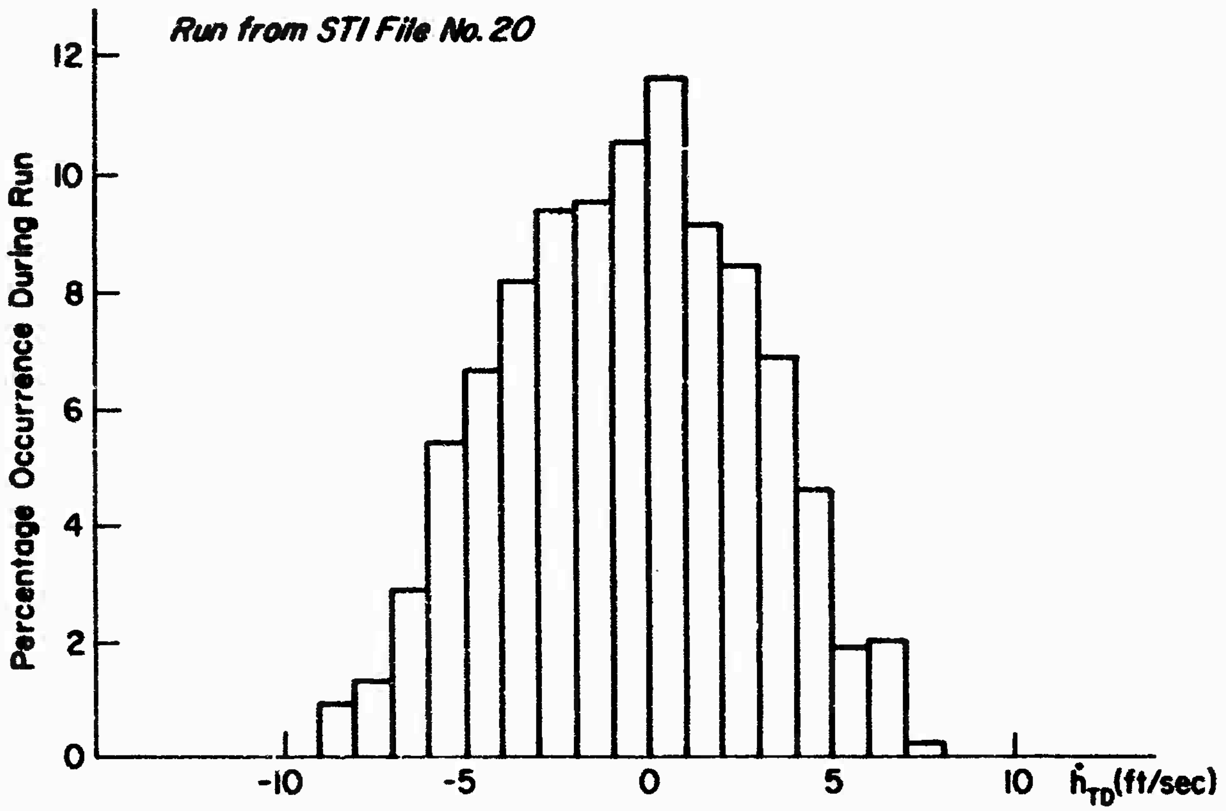


Figure C-7. Distribution of Amplitudes (From Mean) of Vertical Velocity of Touchdown Point ($\dot{h}_{TD}$) in Ft/Sec

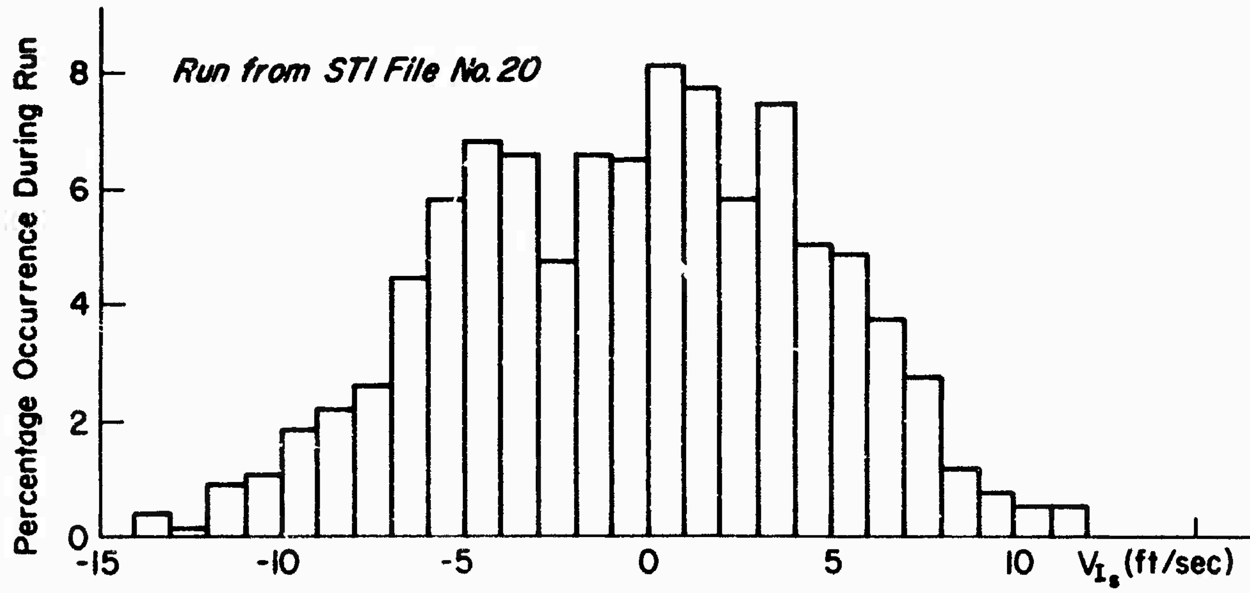


Figure C-8. Distribution of Amplitudes (From Mean) of Impact Velocity Due to Ship Motion (V_{I_S}) in Ft/Sec

APPENDIX D

SPECTRAL PROPERTIES OF THE SHIP MOTION VARIABLES

This appendix consists of power spectral density plots of the ship motion variables during a representative selection of time intervals. Table D-I presents a list of the file numbers for the PSD plots that are included.

TABLE D-I

LIST OF THE FILES FOR WHICH POWER SPECTRAL DENSITY, $\Phi(\omega)$, PLOTS ARE PRESENTED IN THIS APPENDIX

VARIABLE	FILES
θ_s	7, 7A, 15, 15A, 17, 17A, 19, 19A, 19B, 20
φ_s	7, 15, 17, 19, 20
h_s	7, 7A, 15, 15A, 17, 17A, 19, 19A, 19B, 20
h_{TD}	20
h_R	20
$h_{TD/2}$	20
$\dot{h}_{TD}$	20
V_{I_s}	20

The PSD plots are scaled such that the following relation applies to each variable.

$$\sigma^2 = \int_0^\infty \Phi(\omega)d\omega$$

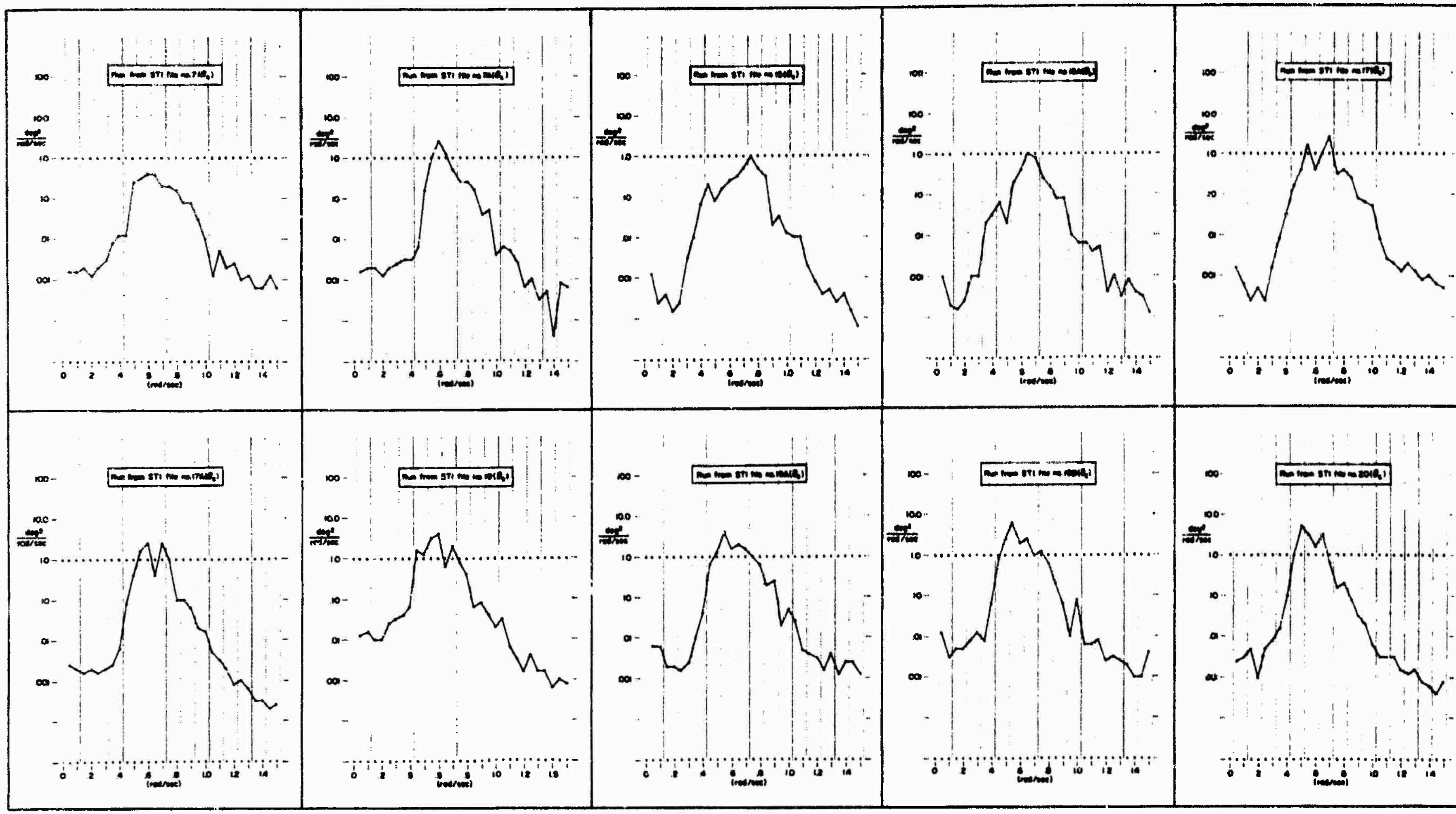


Figure D-1. Power Spectral Density of Ship Pitch Angle (θ_s)

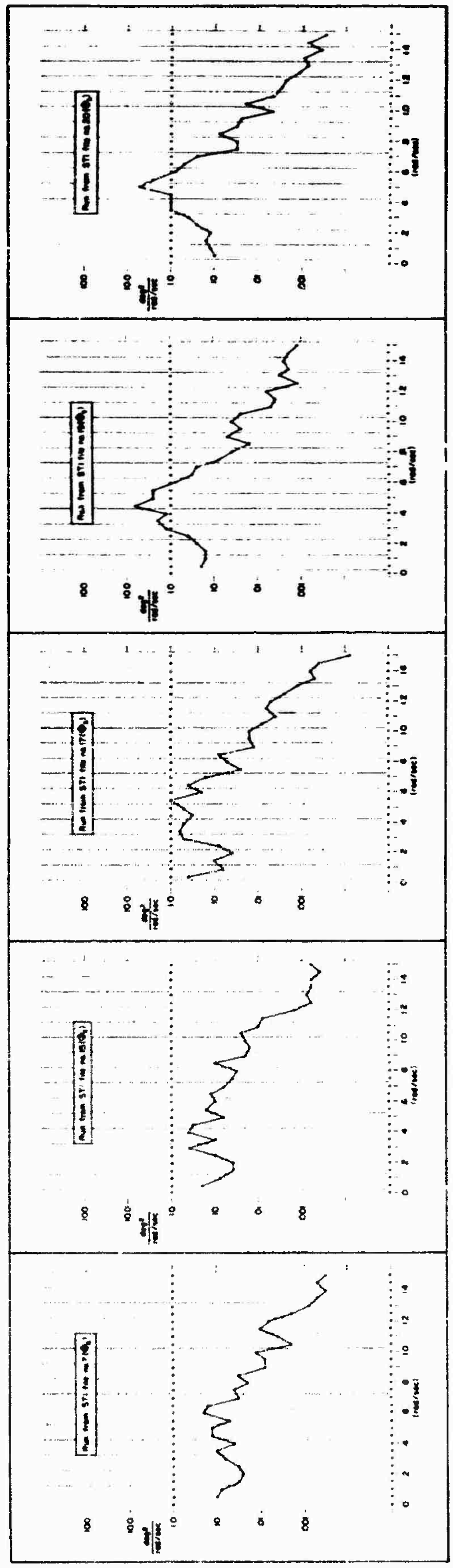


Figure D-2. Power Spectral Density of Ship Roll Angle (φ_s)

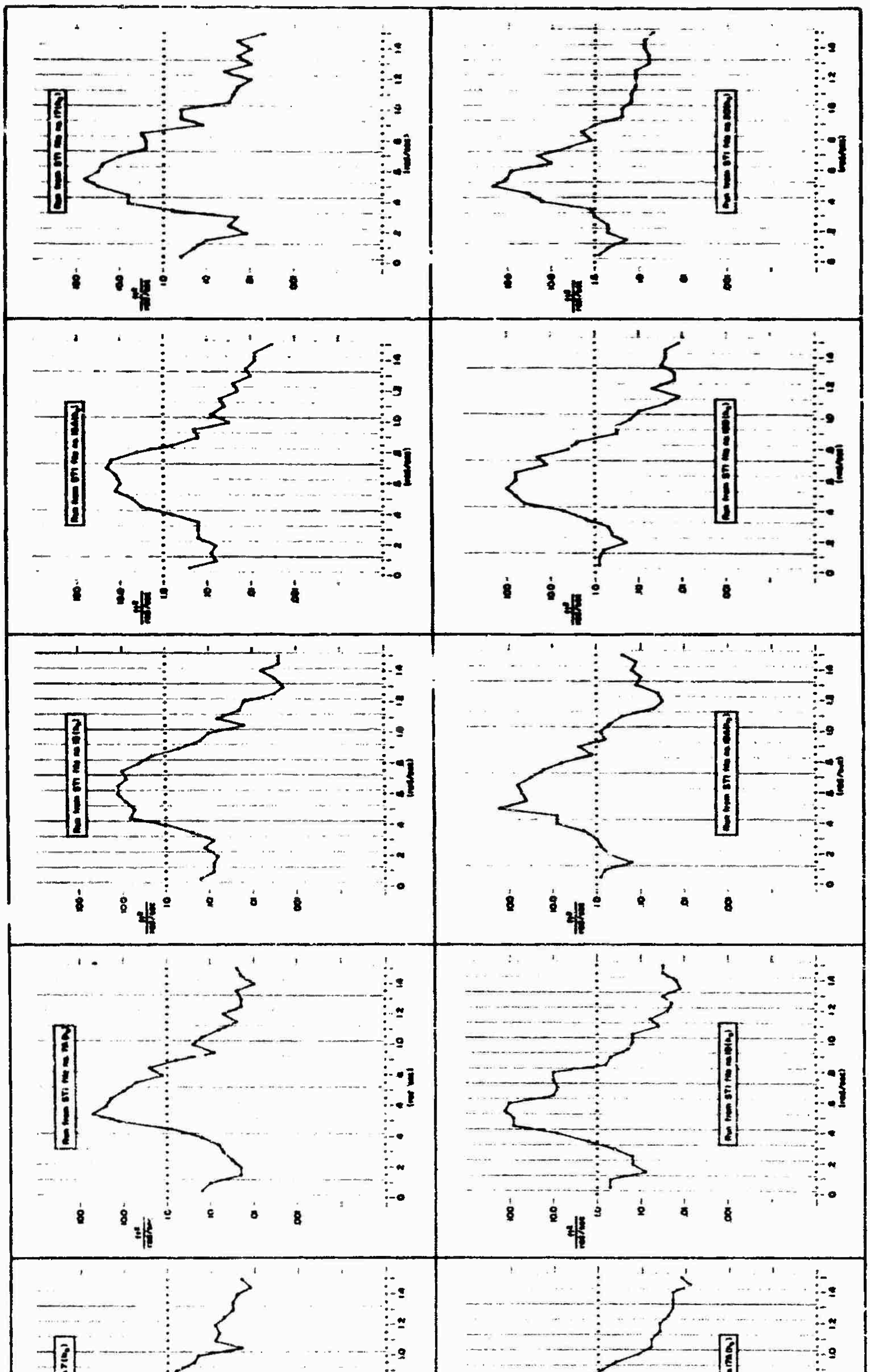


Figure D-3. Power Spectral Density of Ship Heave (h_s)

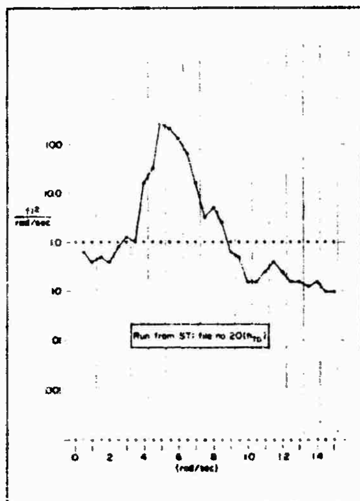


Figure D-4

Power Spectral Density of Vertical Displacement of Touchdown Point (h_{TD})

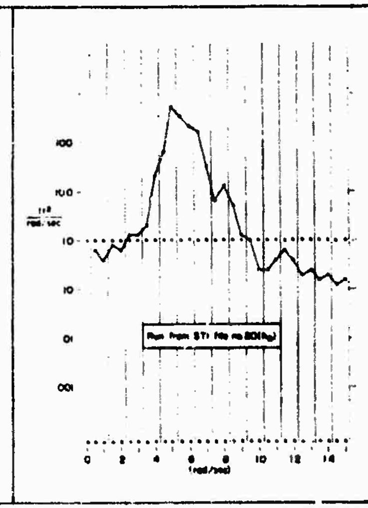


Figure D-5

Power Spectral Density of Vertical Displacement of Ramp (h_R)

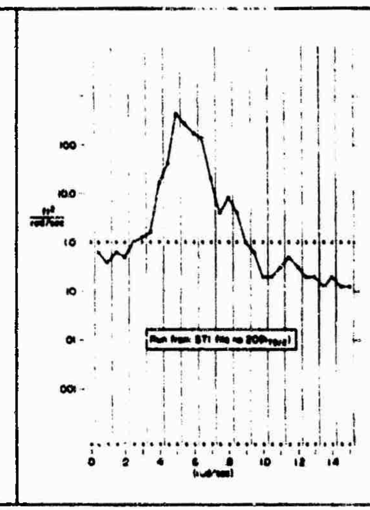


Figure D-6

Power Spectral Density of Vertical Displacement of Point on Deck One-Half Way Between Ramp and Touchdown Point ($h_{TD/2}$)

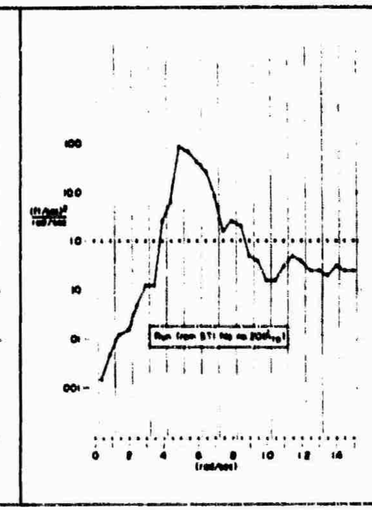


Figure D-7

Power Spectral Density of Vertical Velocity of Touchdown Point ($\dot{h}_{TD}$)

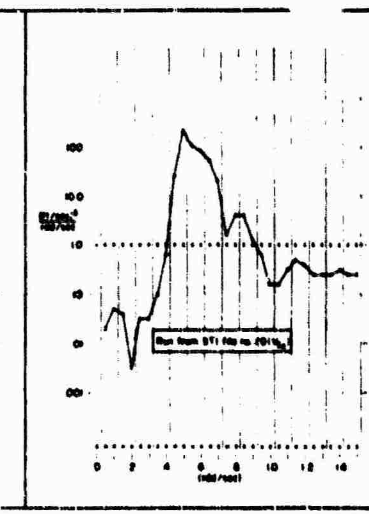


Figure D-8

Power Spectral Density of Effective Impact Velocity Due to Ship Motion (V_{I_s})

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13. ABSTRACT

Carrier landing operations are often suspended due to severe deck motions. Attempts to compensate for deck motions require detailed knowledge of the nature of such motions over short time intervals (because a landing approach typically lasts only 30 sec). This report contains the results of examining ship motion amplitude and frequency characteristics over short time periods in rough sea conditions. Included are histograms and power spectral density plots of pertinent recorded ship motions. These are presented for several short intervals over a three hour period so that a variation of motion characteristics with time is evident.

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